Oil and gas pipeline distribution networks – A new approach to access their vulnerability and risk

J. Pinto[a], H. Varum[b], J. Varajão[c], I. Bentes[d]

[a] Jorge Pinto. Mailing address: Departamento de Engenharias, ECT, Universidade de Trás-os-Montes e Alto Douro, Apartado 1013, 5001-801 Vila Real, Portugal. (*E-mail: tiago@utad.pt*)
[b] Departamento de Engenharia Civil, Universidade de Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro. Portugal. e-mail: (*E-mail: hvarum@ua.pt*)
[c] Departamento de Engenharias, ECT, Universidade de Trás-os-Montes e Alto Douro, Apartado 1013, 5001-801 Vila Real, Portugal. (*E-mail: joao@varajao.com*)
[d] Departamento de Engenharias, ECT, Universidade de Trás-os-Montes e Alto Douro, Apartado 1013, 5001-801 Vila Real, Portugal. (*E-mail: ibentes@utad.pt*)

Abstract

The main objective of this research work is to introduce the emerging theory of vulnerability of water pipe networks and, in particular, its theoretical concepts, extrapolating them to the oil and gas pipeline distribution network fields. This expansion is almost direct and could give an important contribution for the design of new network systems, as well as for the assessment, rehabilitation and management of the existing networks and systems. The fundamental contributions of this theory are to design network pipelines more robust but also to give guidance to the technical community in order to achieve a more efficient management of this type of systems. Some highlights on risk assessment and failure scenarios of this type of systems are also given in this paper.

Keywords: oil and gas pipeline networks, vulnerability, failure, risk

1. INTRODUCTION

The structural vulnerability theory (SVT) has been developed recently in Bristol University, UK, [1-6]. This theory is able to identify the vulnerable parts of a structure in which vulnerability concept is associated to the possible existence of a disproportionately between failure demand and structural failure consequence. A structure is vulnerable when a small damage demand leads to a disproportionately structural failure consequence. The action that may cause that failure can be any type including human error or even accidental loads. The SVT is a theory of structural form and connectivity.

On the other hand, another research work, which has been developed in Trás-os-Montes e Alto Douro University (UTAD), Portugal [7-9], has been focused on extrapolating these theoretical fundaments into the water pipe networks (WPN) context resulting in an emerging theory of the vulnerability of water pipe networks (TVWPN). Several research studies have been done in order to predict the probability of the occurrence of failures in WPN [10] and also concerning the vulnerability of WPN based upon fuzzy models [11]. However, the TVWPN can be used for the evaluation of vulnerability in a much more transversal approach, considering all the factors that influence the vulnerability and risk.

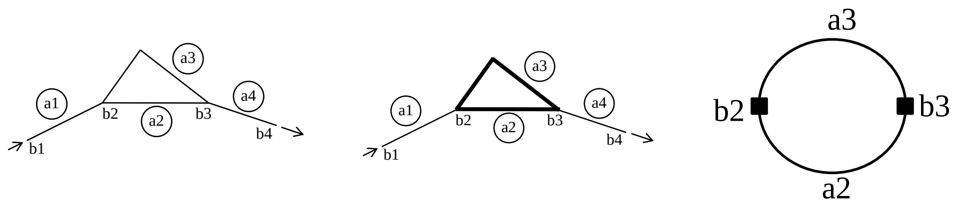
The main objective of this paper is to present the TVWPN and to give guidance for its future extrapolation for the oil and gas pipeline distribution networks, which may have an important contribution on the design phase of these networks and associated systems, or even in the assessment, rehabilitation and management processes of the existing ones.

Since the TVWPN can be adopted to access the scale of damage resulting from a certain vulnerable scenario, the inherent risk may also be calculated by quantifying the probability of occurrence of that vulnerable failure scenario. Therefore, its adaption to the oil and gas pipeline distribution networks can be of great interest for a more rigorous safety assessment and emergency action planning.

2. THE BASIC THEORETICAL CONCEPTS OF THE TVWPN

A system is a set of interacting objects which are process holons [12-13]. The objects are arranged and connected together in some appropriate form. A *graph model* represents a system in terms of nodes and links. In a WPN system, Figure 1-a, nodes are the joints and links are the pipelines.

Figure 1. System, cluster and ring in the WPN context



a) WPN system b) WPN cluster c) WPN ring

Key: a – Link object; b – Node object

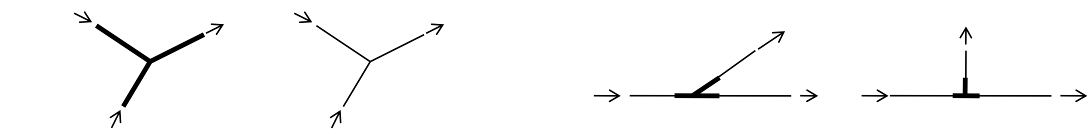
A *cluster* is a subset of the graph model in which the objects are in some sense more tightly connected to each other than to other objects outside of the cluster. A *WPN cluster* is considered of being a subset of the WPN in which the pipelines are in some sense more tightly connected to each other than the other pipe lines outside of the WPN cluster, Figure 1-b.

A *WPN ring* is assumed of being a maximum of two connected WPN clusters which can supply water between different points, Figure 1-c. A *WPN leaf cluster* (or WPN primitive cluster) contains a single pipeline and adjacent joints. A *WPN branch cluster* is a cluster that contains more than one leaf cluster, a sub-WPN is a branch cluster. A *WPN ring* is a WPN branch cluster. The *WPN reference cluster* is the storage tank which is the cluster from which the WPN is separated for the total failure scenario to occur. The *WPN root cluster* contains the entire WPN including the reference cluster. A *WPN deteriorating event* may be the damage that results from any type of action which causes the loss, by a WPN ring, of the capacity to supply good quality of water between points, it may be the collapse of a pipeline, an obstruction or even, but extremely important, the degradation of water quality. Thus, a *WPN vulnerable failure scenario* is considered of being an ordered sequence of WPN deteriorating events by which the performance of a WPN decreases. In both contexts, the action may be any kind including human error in use or even accidental natural actions.

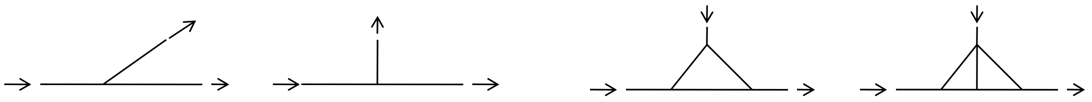
2.1 Well formedness

The *well formedness* of a WPN cluster is assumed of being the measure of the quality of the form of a WPN which is independent of the co-ordinate system. In some way, it has to be related to the stiffness of the pipelines (Figure 2-a), the type of the joint (Figure 2-b), the configuration of the WPN (Figure 2-c) and the connection between the pipelines (Figure 2-d).

Figure 2. Factors that may influence the well formedness of a WPN



a) Stiffness of the pipelines b) Type of the joint



c) Configuration of the WPN d) Connection

Taking into account all the possible variables which are considered in the design of a WPN and according the classical theories and, based on an exhaustive study, we propose that the total head losses (ΔH_T), Expression 1, was proposed as being the indicator of the well formedeness of a WPN because it includes indirectly all the above factors, Figure 2. A small total head losses indicates a good form of a WPN branch cluster.

$$\Delta H_T = \sum_{j=1}^{p} \Delta H_j + \sum_{i=1}^{u} \Delta H_{L_i} \qquad (1)$$

where ΔH_T is the total head losses, the ΔH is the occurred head losses in the j pipeline, ΔH_L is shock losses, p is the total number of pipelines existing in the WPN branch cluster and u is the total number of shock losses existing in the WPN branch cluster.

2.2 Nodal connectivity

In the WPN context, the *nodal connectivity* (η) of a WPN branch cluster measures the connection of that WPN branch cluster and the rest of the WPN or, in other words, the existing alternative water supplying paths between that WPN branch cluster and the rest of the WPN. It also represents the likelihood of that WPN branch cluster forming WPN rings with the others branch clusters of the rest of the WPN. At this stage, the η of a WPN branch cluster is the sum of the all pipelines, outside of the cluster, that converge to the joints of that WPN branch cluster.

2.3 Damage demand

The *WPN damage demand* (E) has been considered, at this stage, of being a measure of the effort required to cause a deteriorating event in the WPN which is proportional to the strength capacity of a pipeline. The strength capacity of a pipeline is function of the material mechanical properties and the area of the cross section. If, by simplification, it is assumed that whole WPN system is built up using the same type of material then the strength capacity of a pipeline becomes only dependent of the cross section area of the pipeline. Considering that a deteriorating event may be a cut of the pipeline, an obstruction or water quality degradation than further research is required to find out a more embracing damage demand measure than the proposed above.

2.4 Relative damage demand

The WPN relative damage demand (E_r) of a WPN failure scenario is the ratio of the WPN damage demand (E) of a failure scenario to the maximum possible damage demand of a failures scenario in the structural system (E_{max}) (i.e. failure scenario in which deteriorating events occur in every WPN primitive clusters).

2.5 Separateness

In the WPN context and taking into account that the well formedness of a WPN branch cluster is proposed here has been related to the total head losses occurred in that WPN branch cluster, the *separateness* (γ_r), in this context, has been defined as a measure of the failure consequence and has been calculated as the ratio of the loss in WPN well formedeness of the deteriorated WPN to the well formedeness of the intact WPN. Total separateness occurs when the WPN system becomes disconnected from the reference cluster and that defines total failure. If the separateness of a failure scenario is equal to 1 then the WPN is unable to supply water to any point. In contrast, if it is equal to 0 then the WPN is totally intact and it is able to supply water to all points.

2.6 Vulnerability index

The WPN vulnerability index (φ) of a failure scenario is a measure of the vulnerability of a WPN and can be measured by the ratio of the separateness (γ_r) to the relative damage demand (E_r). It is a measure of the disproportionateness of the consequence (the separateness) to the damage (the damage demand). An expressive value of φ related to a certain failure scenario indicates that the WPN shows signs of high vulnerability because there is a disproportionate relation between the extension of the deterioration of the WPN and the effort required to cause that damage and, this fact, may give guidance for the management of the WPN for instance.

3. APPLICATION OF THE TVWPN

The application of the TVWPN to a WPN consists on three main stages that are the clustering process, the hierarchical model formation and the unzipping process.
In brief, the clustering process consists on a progressive formation of WPN branch clusters that are tightly connected, starting at the first level by only using primitive clusters (pipelines) and finishing, at the last level, by having the whole WPN, including the storage tank, completely agglutinated (resulting in a WPN branch cluster). It is a selective process that requires criteria which are identified in the next section.

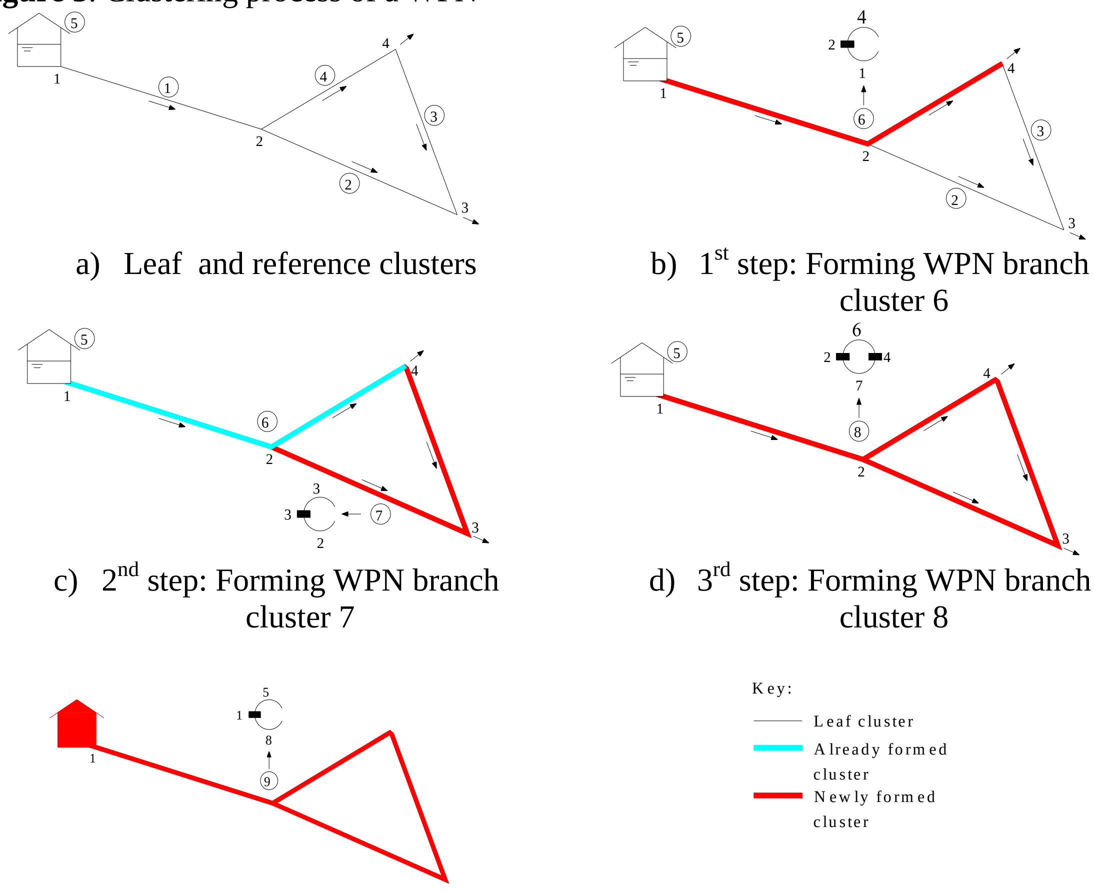
Based upon the information resulted from the clustering process it is possible to build the hierarchical model of the WPN which is an abstract way of representing the WPN in a interconnected and well formedness bases. It is by this model that the vulnerable failure scenarios are identified through the unzipping process. The unzipping process is the last stage of the application of the TVWPN. Unzipping the hierarchical model from the top to the bottom and using criteria, WPN deteriorating events are found with the purpose of identifying vulnerable failure scenarios. These vulnerable failure scenarios allow than to identify the part of the WPN that are more vulnerable.

3.1 Clustering process

As it was stated, the clustering process is a progressive and a selective process which consists of identifying WPN rings made up of joints and pipeline at the first and familiar level of definition of a WPN. A new set of WPN rings of clusters is then formed to provide a second level of definition of the WPN. The process of clustering is repeated to form even higher levels of definition in a hierarchy until a single WPN cluster, the whole WPN including the storage tank remains.

This process uses five clustering criteria which are applied to decide the next WPN branch cluster to be formed in each level of definition. These five clustering criteria are in order the following: the minimum total head losses (ΔH_{Tmin}); the maximum damage demand (E_{max}); the maximum nodal connectivity (η_{max}); the maximum distance from the storage tank (D_{ISmax}); free choice (F_C). In order to exemplify the application of the clustering process and to complement the above description Figure 3 shows graphically the application of this process to a simple WPN.

Figure 3. Clustering process of a WPN



a) Leaf and reference clusters

b) 1st step: Forming WPN branch cluster 6

c) 2nd step: Forming WPN branch cluster 7

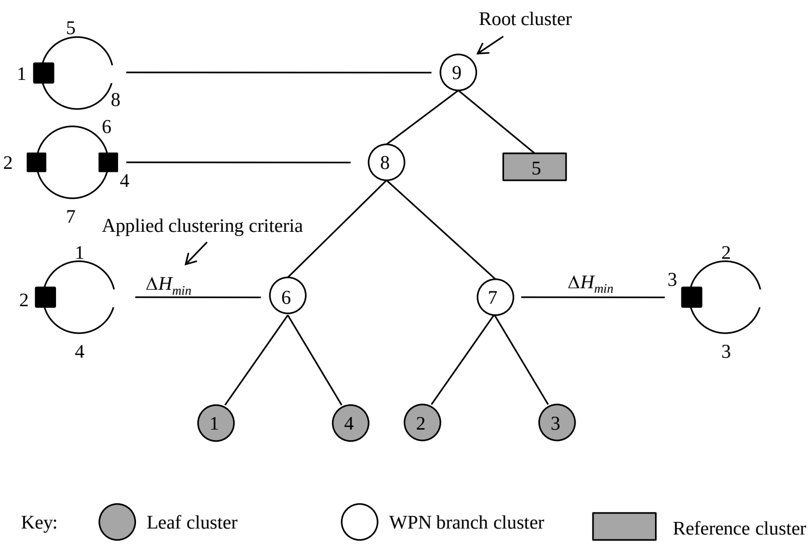
d) 3rd step: Forming WPN branch cluster 8

e) 4th step: Forming WPN branch cluster 9

3.2 Hierarchical model formation

The hierarchical model is another alternative graphical way of representing a WPN. However, the WPN elements (joints and pipelines) appear in that model rearranged according to the quality of the form of the WPN and resulted from the previously applied clustering process. Figure 4 shows the hierarchical model of the WPN of Figure 3.

Figure 4: The hierarchical model of a WPN



The interpretation of a hierarchical model has to start from the bottom to the top. Going up from the bottom to the top of the hierarchical model the new WPN branch clusters that were formed during the clustering process and the respective primitive clusters used are clearly identified. Simultaneously, the WPN rings that represent these new WPN branch clusters and the applied clustering criteria used for the candidate selection are also shown. The part of the WPN that is represented in the bottom of the hierarchical model has better form than the others parts that are represented above. This model is extremely important for the last stage of the application of the TVWPN, the unzipping process, and as it will be detailed explained during the following section.

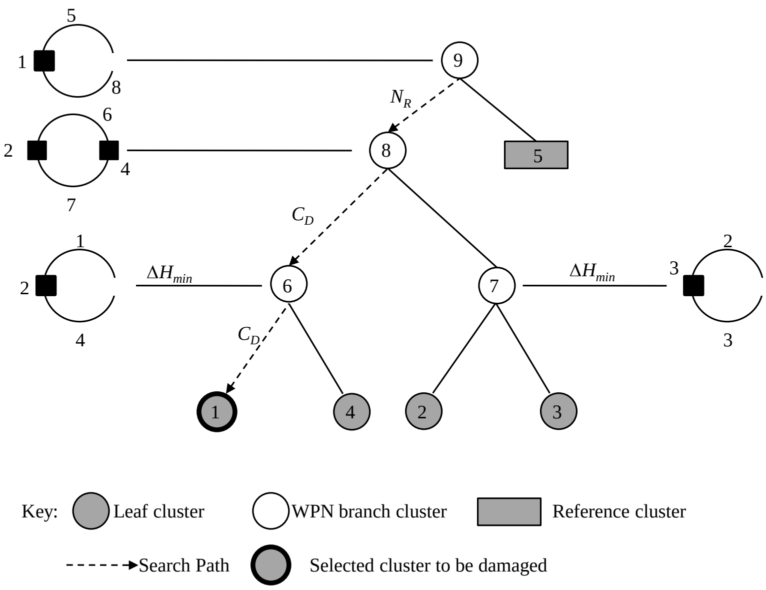
3.3 The unzipping process

The unzipping process is the third and the last stage of the application of the TVWPN which uses the hierarchical model of a WPN as the base for searching the vulnerable WPN failure scenarios. The hierarchical model is unzipped from the top to the bottom focusing on all the existing WPN branch clusters. Each WPN branch is unzipped in turn and deteriorating events are found until that WPN branch cluster or the whole WPN becomes totally inoperative. Meanwhile, always that a deteriorating event is found, the WPN branch cluster changes and, therefore, it is required to cluster and to define the respective new hierarchical model of the changed WPN branch cluster. This fact indicates that the unzipping process is an iterative process. The ordered sequence of deteriorating events resulted by this process define the vulnerable failure scenarios found by the TVWPN. For the search of deteriorating events, the unzipping process also uses criteria (unzipping criteria).

The unzipping criteria are, by ordered of application, the following: is not the reference cluster (storage tank), N_R; connects directly to the reference cluster, C_D; is a leaf cluster (or a primitive cluster or a pipeline) rather than WPN branch cluster, L_C; has the higher value of head losses, $S_{\Delta H}$; has the smallest damage demand, S_E; was clustered the latest, C_L; free choice, F_C. At this stage of the research and, by simplification, the storage tank is considered of being undamaging. If a pipeline connects directly to the storage tank then it is likely that its loss will result in a disproportional failure consequence of the WPN. It is possible to identify a deteriorating even in a leaf cluster (i.e. a pipeline) rather than a branch cluster.

Through this process the vulnerable failure scenarios of a WPN are identified which are the following: *Total failure scenario* is the one where least effort is required for the whole WPN to become inoperative (there is no water supplying to any point). Among the failure scenarios identified with separateness equal to 1, the total failure scenario is the one that has higher value of vulnerability index (φ); *Maximum failure scenario* is the one that results in maximum damage from least effort and it is not necessary the total. Among the failure scenarios found the maximum failure scenario is the one that has the highest value of φ. The maximum failure scenario is related to the most vulnerable part of a WPN; *Minimum failure scenario* is related to the worst well formed part of a WPN and, in generally, corresponds to the last leaf cluster to be clustered in the clustering process; *Minimum demand failure scenario* is related to the weakest part of a WPN to suffer damage. Corresponds to the leaf cluster that has the smallest value of damage demand; *Interesting failure scenario* is the one in which the designer is specifically interested for local reasons such as sensitivity to particular usage. Figure 6 shows one step of the unzipping process of a WPN.

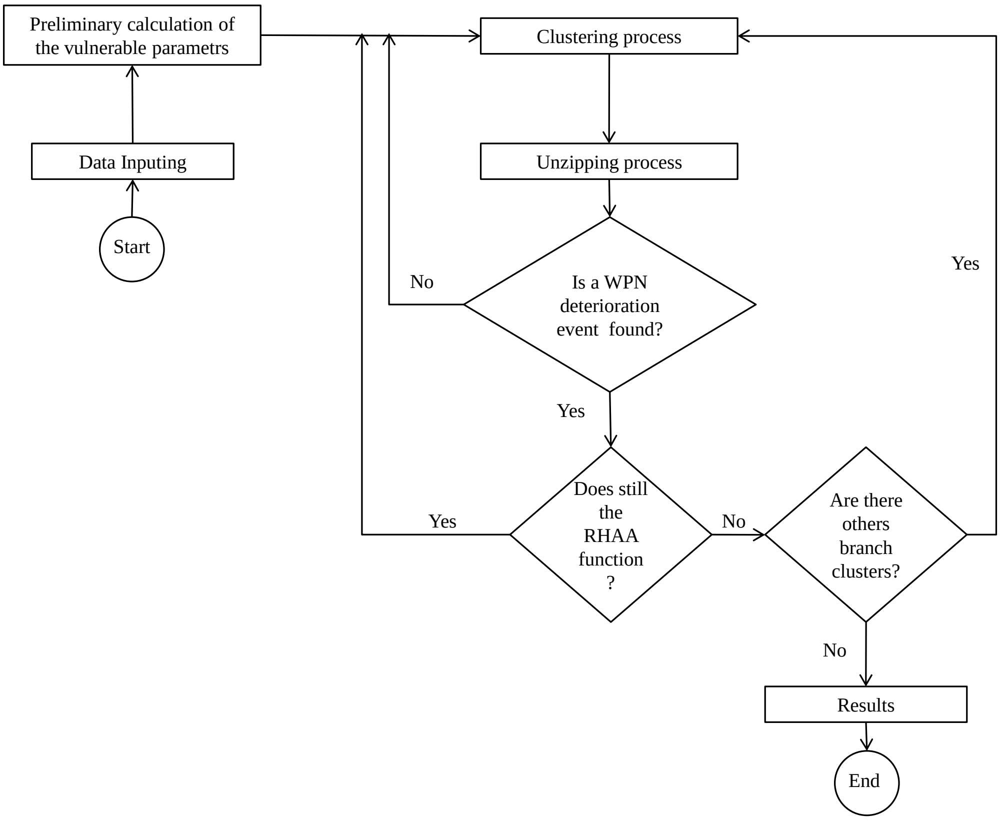
Figure 6. A step of the unzipping process of a WPN



4. COMPUTER PROGRAM VWPN

In order to stimulate the application of the TVWPN a computer program designated by Vulnerability of Water Pipe Networks (VWPN) has been developed in UTAD using C code (GCC, version 4.2, 2000). The frame of the VWPN is basically formed by five blocs, Figure 6, as following: 1) Data imputing: introduction of the data related to the WPN; 2) Preliminary calculation of the vulnerable measures; 3) Clustering process; 4) Unzipping process; 5) Output: numerical and graphical results.

Figure 6. Flowchart of the computer program VWPN



5. RISK OF A WPN VULNERABLE FAILURE

Based on [14] risk as being defined as the combined effect of the chances of occurrence of some failure or disaster and its consequences in a given context, Expression 2.

$$R(Context) = p \times Con \tag{2}$$

where *R(Context)* is the risk of a failure in a given context, *p* is the chance of a failure and *Con* is the consequence of a failure.

According to [6], within the totality of all possible modes of failure (including business and financial failure) the structural risk (*SR*) is defined as one aspect (structural functionality) of the total project risk as:

$$SR = pfs \times SCon \tag{3}$$

where *pfs* is the probability of failure which is calculated using the techniques of structural reliability analysis and *SCon* is a function of structural separateness.

In the WPN context the associated WPN risk (*WR*) may be defined as following:

$$WR = pfw \times WCon \tag{4}$$

where *pfw* is the probability of WPN failure and *WCon* is a function of the WPN separateness (section 2.5).

6. EXTRAPOLATING THE TVWPN TO THE OIL AND GAS PIPELINE DISTRIBUTION NETWORK FIELDS

Apart of water, oil and gas being different substances, but all of them fluids. The water, oil and gas distribution networks systems have a lot of similarities in terms of function, structural behaviour, design theories and construction processes among others.

Based on the above facts, authors suggest in this paper the extrapolation of the TVWPN to the oil and gas pipeline distribution network fields. The well established concept and tools (section 2.1) should be adapted for these new contexts. The separateness concept (section 2.5) may also need to be extended in order to take into account relevant aspects related specifically to the oil and gas pipeline distribution network fields, such as environmental pollution disasters and financial losses.

7. MAIN CONCLUSIONS

The theory of the vulnerability of water pipe networks (TVWPN) was introduced and slightly described. The main purposed of the TVWPN is to identify the most vulnerable parts of water pipe networks (WPN) and consequently to increase robustness of this kind of system. This theory may be applied in the design, maintenance and management of the WPN systems. In order to simply its application a computer programme has been developed in UTAD. This theory may give a value of the scale of failure consequence resulting from a vulnerable failure scenario through the separateness concept. This information allows to access the risk associated to that failure scenario.

This theory and tools may be directly extrapolated to the oil and gas pipeline distribution networks, which may have an impressive contribution at his design phase, as well as for the assessment, rehabilitation and management of the existing networks and systems.

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